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A 14.6 Arcsecond Quasar Lens Split by a Massive Dark Matter Halo

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Gravitational lensing is a powerful tool to study the distribution of dark matter in the universe. The cold dark matter model of structure formation

predicts^{1–6} the existence of quasars gravitationally lensed by concentrations of dark matter⁷ so massive that the quasar images would be split by over $7''$. However, numerous searches^{8–11} for large-separation lensed quasars have been unsuccessful; all of the roughly 70 lensed quasars known to date¹², such as Q0957+561¹³, have smaller splittings, and can be explained in terms of galaxy scale concentrations of baryonic matter that have undergone dissipative collapse. Here we report the discovery of the first large-separation lensed quasar, SDSS J1004+4112, with a maximum separation of $14''.62$; at this separation, the lensing object must be dominated by dark matter. While gravitationally lensed galaxies¹⁴ of even larger separation are known, large-separation quasars are more useful cosmological probes because of the simplicity of the resulting lens systems. The discovery in current our quasar sample is fully consistent with the theoretical expectations^{3–5} based on the cold dark matter model.

For bright quasars ($i \lesssim 19$), the probability of gravitational lensing¹⁵ is only about 0.1%; the majority of these lenses have small separations, due to a single massive galaxy. The fraction of large-separation lensed quasars is predicted to be 0.01% or less^{3–5}; thus it is not surprising that none have been found to date^{8–11}. In order to find such objects, we need samples of tens of thousands of quasars, such as generated by the Sloan Digital Sky Survey^{16,17} (SDSS). The SDSS is conducting both a photometric survey^{18–22} using five broad optical bands²² (u , g , r , i , and z) and a spectroscopic survey²³ of 10,000 square degrees of the sky centered approximately on the North Galactic Pole, using a dedicated wide-field 2.5-m telescope at the Apache Point Observatory.

We searched for large-separation lensed quasars in a sample of $\sim 29,500$ spectroscopically-confirmed SDSS quasars²⁴ at $0.6 < z < 2.3$, a sample roughly three times larger than those used in previous searches. Even with this large sample, the expected number of large-separation lensed quasars is of order unity. In the field around each quasar in the sample, we searched for stellar objects with colors differing by less than 0.1 from those of the quasar, with separations between $7''.0$ and $60''.0$ and with flux greater than one tenth that of the quasar. SDSS J1004+4112 was identified as a “quadruple” large-separation lensed quasar candidate using these criteria. Only one of the four components (component B, see below) has an SDSS spectrum (the SDSS hardware²³ does not allow pairs of objects separated by less than $55''$ to be observed on a single plate), and therefore, we obtained spectra of all four components using the Keck I telescope at the W. M. Keck Observatory. The results are shown in Figure 1. All four components indeed show quasar-like features, with all emission lines giving a consistent redshift $z = 1.734 \pm 0.002$; the velocity differences of the quasar components are $\sim 100 \text{ km s}^{-1}$, comparable to the observational uncertainty. Although it is not obvious from Figure 1, there are C IV absorption line systems at $z=1.732$ in each

of the four quasar spectra; this is an absorption system associated with the quasar itself, further supporting the lensing hypothesis: the four quasar images are from the same physical source. The differences in their spectra may be explained by the modest time-variability of the source quasar over ~ 1 year, the expected gravitational lensing time-delay²⁶ among those different images.

Additional strong support for the lensing hypothesis comes from the identification of the galaxy cluster responsible for the large-separation lensed quasars. From the observed image separations (the maximum separation is $14''.62$, between images B and C), one can infer that the lensing object should have a velocity dispersion in excess of 600 km s^{-1} . Thus the lensing object cannot be a single galaxy, but must be rather a group or cluster of galaxies which has a sufficiently concentrated distribution of dark matter. To identify the lensing object, we obtained deep optical images of the system using the Subaru telescope of the National Astronomical Observatory, Japan. The result is shown in Figure 2. A number of galaxies are clearly detected around component G, suggesting that it is the most luminous galaxy of the cluster. We obtained a spectrum of component G using the Keck I telescope. The spectrum shows a number of absorption features characteristic of a late-type galaxy at a redshift of $z = 0.6799 \pm 0.0001$. We also obtained spectra of two faint galaxies immediately to the south-west of component G (Figure 2) using the Faint Object Camera and Spectrograph²⁸ of the Subaru telescope. The redshifts of these two faint galaxies are $z = 0.6751 \pm 0.0001$, strongly suggesting a cluster of galaxies at $z \sim 0.68$ centered on component G. Clusters are dominated by elliptical galaxies, which all have very similar spectral energy distributions. Many of the faint galaxies in Figure 2 (~ 40 galaxies around component G) have colors that are similar to that of component G. The colors are consistent with the expected colors of elliptical galaxies at $z \sim 0.68$ ($g - r \sim 1.8$ and $r - i \sim 1.1$). In addition, there is an X-ray source in this direction detected by the ROSAT All-Sky Survey²⁹ (0.236 counts per second in a 473 seconds exposure). The emission, however, comes most probably from the quasar, because the detected X-ray flux is too strong for typical clusters of galaxies at $z = 0.68$. Finally, we note two possible arclets (highly distorted images of background galaxies due to gravitational lensing) in Figure 2 (marked as “arc?”) close to component D. If future observations confirm that the arclets are indeed lensed background galaxies, they will provide strong additional constraints on the total mass distribution of the lensing cluster.

The lensing interpretation is further supported by a theoretical model of SDSS J1004+4112. We fit the positions of the four quasar components with a singular isothermal ellipsoid (SIE) plus external shear model using the Lens Modeling Software³⁰. The best fit model is illustrated in Figure 3. The positions and relative brightnesses of all components agree well with the lens model predictions. The center of the lensing mass is offset from the center of component G by about 10 kpc at the cluster redshift, but brightest cluster galaxies are not

always found exactly at the center of the potential wells of their clusters.

The identical redshifts ($z = 1.734$) and the spectral energy distributions of the four lensed components, the existence of a lensing cluster of galaxies ($z \sim 0.68$), and the presence of possible arclets confirm the hypothesis that the quasar is lensed by this cluster. Furthermore, a theoretical lensing model involving the cluster and external shear simultaneously accounts for the observed geometry of the system and the relative brightness of the images. This is the first unambiguous discovery of a long predicted but previously undetected population of large-separation lensed quasars.

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Table 1. **ASTROMETRY AND PHOTOMETRY FOR SDSS J1004+4112**

Object	R.A.(J2000) ^a	Dec.(J2000) ^a	g^b	r^b	i^b	z^b	$\Delta\theta^c$
A	10 04 34.794	+41 12 39.29	18.67±0.03	18.70±0.02	18.46±0.02	18.43±0.05	3''73
B	10 04 34.910	+41 12 42.79	19.05±0.06	19.10±0.06	18.86±0.06	18.92±0.06	0''00
C	10 04 33.823	+41 12 34.82	19.71±0.03	19.73±0.02	19.36±0.03	19.31±0.07	14''62
D	10 04 34.056	+41 12 48.95	20.67±0.04	20.51±0.04	20.05±0.04	20.00±0.13	11''44
G	10 04 34.170	+41 12 43.66	22.11±0.40	20.51±0.13	19.54±0.09	19.04±0.21	8''44

^aR.A. means right ascension (hour minute second) and Dec. means declination (degree arcminute arcsecond). These celestial coordinates were measured on the basis of the celestial coordinates of component B. The positional errors of components A, C, and D (not including the absolute positional errors of component B) are 0''01 and that of component G is 0''05 per coordinate.

^b g , r , i , and z mean the magnitudes of each band.

^cSeparation angles relative to component B

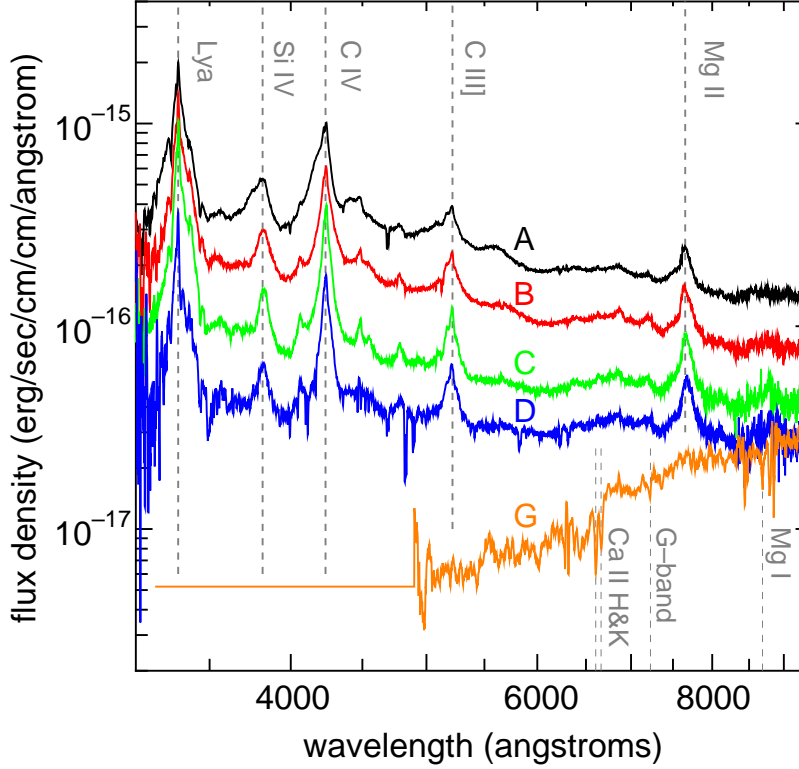


Figure 1 The Keck spectra of the four quasar components A–D and the brightest galaxy G in the lensing cluster. See Figure 2 for these identifications (A–D, and G). The data were taken using the Low-Resolution Imaging Spectrometer²⁵ (LRIS) of the Keck I telescope. The exposure times were 900 seconds for each component. The dispersion is $1.09 \text{ \AA pixel}^{-1}$. The data were reduced in a standard method using IRAF (IRAF is the image reduction and analysis facility, distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation). The black solid line, the red solid line, the green solid line, and the blue solid line represent the spectra of components A, B, C, and D, respectively. The vertical gray dotted lines (3323.6 \AA , 3818.7 \AA , 4235.1 \AA , 5218.5 \AA , and 7651.8 \AA) represent the positions of emission lines of the respective ions red-shifted to $z = 1.734$ of $\text{Ly}\alpha$ (1215.67 \AA), Si IV (1396.76 \AA), C IV (1549.06 \AA), C III] (1908.73 \AA), and Mg II (2798.75 \AA), respectively. All emission lines are clearly at the same redshift. The orange solid line represents the Keck spectrum of component G at the same dispersion. The exposure time was also 900 seconds for component G. The vertical thin gray dotted lines (3933.7 \AA , 3968.5 \AA , 4304.4 \AA , and 5175.3 \AA) represent the positions of absorption lines of the respective ions red-shifted to $z = 0.680$ of Ca II H\&K (3933.7 \AA and 3968.5 \AA), G-band (4304.4 \AA), and Mg I b-band (5175.3 \AA), respectively. There are no data below $\sim 4900 \text{ \AA}$ in the spectrum of component G.

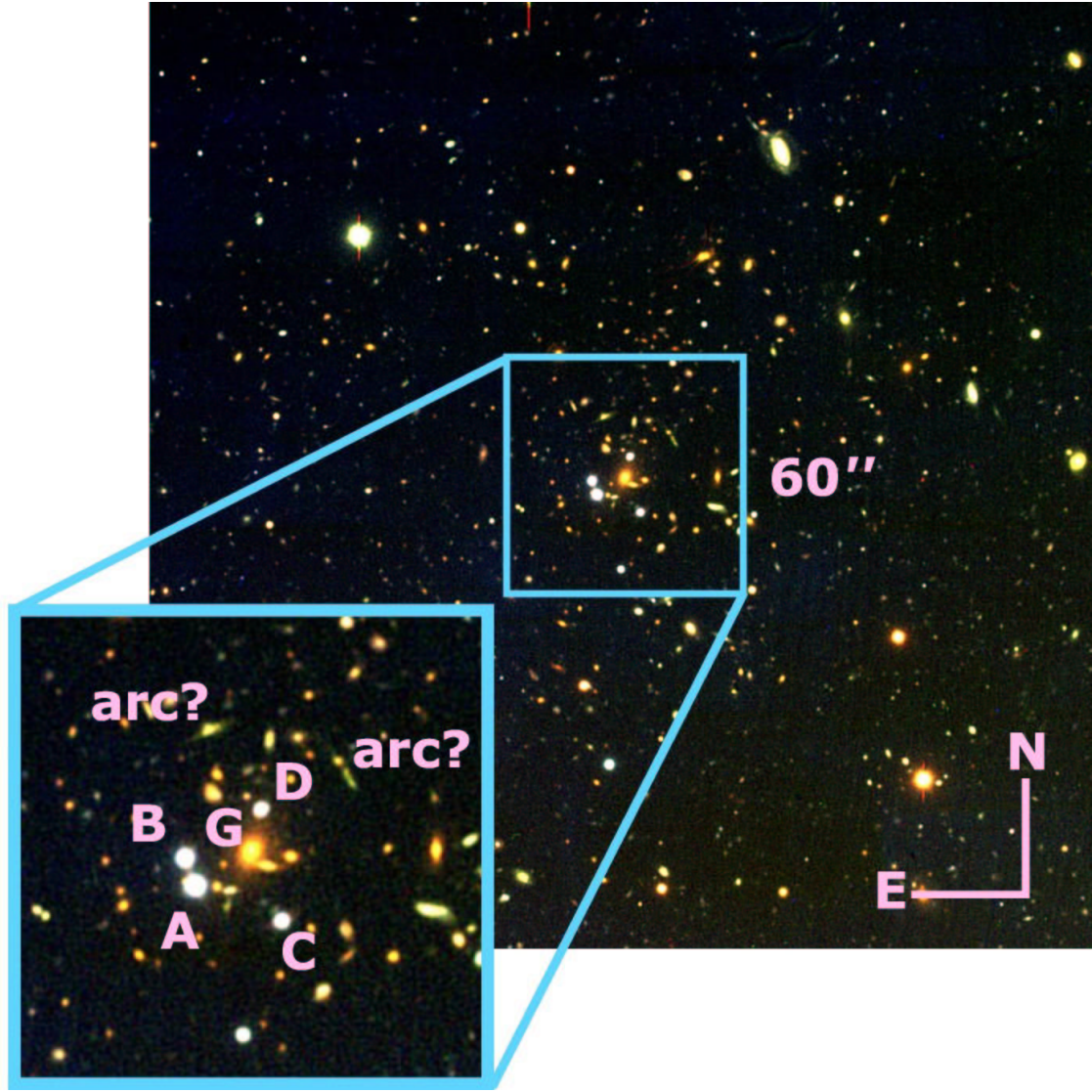


Figure 2 The *gri* composite Subaru image of the field around SDSS J1004+4112. The data were taken using the Subaru Prime Focus Camera²⁷ of the Subaru telescope. The magnitude limit is $i \approx 26.0$. The central 60'' square is shown in an expanded view. The four quasar components are marked as A, B, C, and D, and the bright galaxy located between the four quasar components is marked as G. The separation between components A and D is 12''.77, and that between components B and C is 14''.62. The positions (J2000) and the magnitudes of the components A–D and the brightest galaxy (component G) are summarized in Table 1. Many faint galaxies can be seen — their positions and colors are consistent with being members of a cluster ($z = 0.68$) centered on component G. Two possible arclets (marked as “arc?”) can also be seen. The seeing had a FWHM of 0''.6.

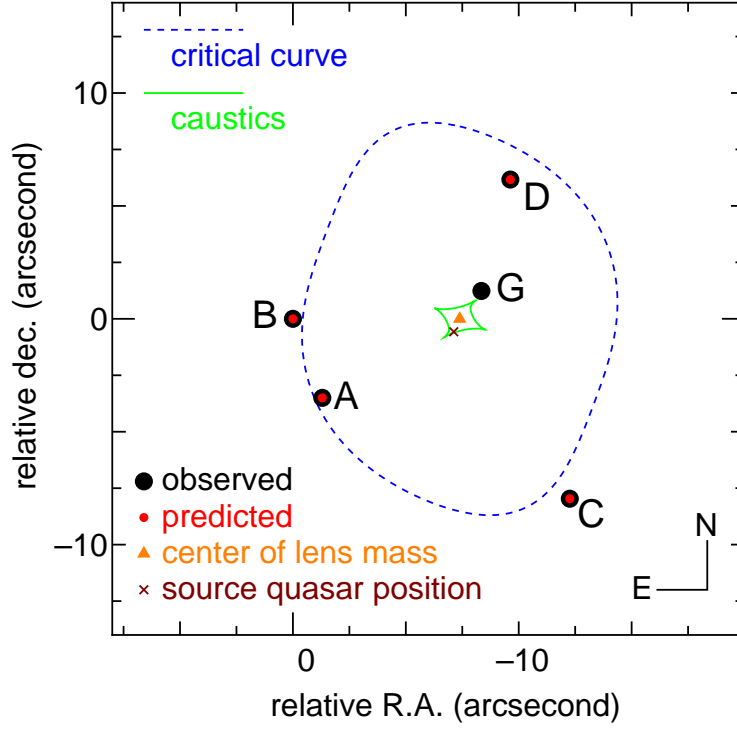


Figure 3 The best fit lens model prediction compared with the observation. We used a lensing model of a singular isothermal ellipsoid with external shear. The best-fit model has an Einstein radius of the SIE model $\alpha_e = 6''.906$ (corresponding to a velocity dispersion $\sim 700 \text{ km sec}^{-1}$ at the cluster redshift), magnitude and position angle of the shear $\gamma = 0.250$ and $\theta_\gamma = -60.925^\circ$ (measured East of North), and ellipticity and its position angle $e = 0.498$ and $\theta_e = 21.434^\circ$ (measured East of North), with a source quasar position $(\Delta\text{R.A.}, \Delta\text{Dec.}) = (-7''.124, -0''.574)$ and a center of lensing mass $(\Delta\text{R.A.}, \Delta\text{Dec.}) = (-7''.387, -0''.004)$ relative to the center of component A. The black filled circles represent the observed positions of components A, B, C, D, and G, and the red filled circles represent the predicted positions of components A–D. The green solid line is the position of the caustic in the source plane, and the blue dashed line represent the critical curve in the image plane. The small orange filled square is the predicted position of the source quasar, and the small gray filled triangle is the predicted position of the center of the lens mass. The differences between the observed and modeled image positions are much smaller than the observational uncertainties. The flux ratios predicted from the model, B/A, C/A, and D/A are 0.78, 0.43, and 0.22, respectively. The total magnification of the quasar images which is predicted by the model is 56.48. The predicted flux ratios are close to the observational results; B/A = 0.69 ± 0.04 , C/A = 0.46 ± 0.02 , and D/A = 0.25 ± 0.01 (measured from the *i* band image). Microlensing by substructures and/or reddening by the Mg II absorption line systems that are seen in each spectrum might be the cause of the differences between the predicted flux ratios and the observations.